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Individual Gait Features Are Associated with Clinical Improvement After Total Knee Arthroplasty

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Background: Over 20% of patients do not report clinically relevant pain relief or functional improvements after total knee arthroplasty (TKA). The aim of this study was to investigate the effect of demographics, pre-TKA knee-joint biomechanics, and postoperative changes in knee biomechanics on meaningful improvements in self-reported pain and function after TKA.

Methods: Forty-six patients underwent 3-dimensional gait analysis and completed the Western Ontario and McMaster Universities Osteoarthritis Index (WOMAC) questionnaire before and 1 year after TKA. Response to treatment in terms of pain relief and functional improvement ("pain and function responders") was defined as improvements in WOMAC scores that met minimal clinically important difference thresholds in the pain and function domains. Differences between responder and non-responder demographics, severity of the osteoarthritis as seen radiographically, and knee kinematics and kinetics before TKA were explored using the t test and Mann-Whitney U test. Correlations and regression models were used to examine demographics, baseline knee kinematics and kinetics, and post-TKA kinematic and kinetic improvements associated with being a pain responder and a function responder separately. Analyses were conducted using a hypothesis-driving approach.

Results: Of the 46 patients, 34 were pain responders and 36 were function responders. Preoperatively, both responder groups had a higher radiographic severity (Kellgren-Lawrence) grade ($p = 0.03$) and pain responders were more symptomatic according to their WOMAC score ($p < 0.04$). Less preoperative stance-phase flexion-extension angle range ($p \leq 0.03$), lower preoperative stance-phase adduction (varus) angle magnitude ($p = 0.01$), and less postoperative reduction in the adduction angle magnitude ($p \leq 0.009$) were independently associated with more self-reported improvement in pain and function.

Conclusions: Patients with a higher radiographic severity grade, with specific frontal and sagittal knee kinematic patterns during gait before TKA, and who demonstrated less reduction in frontal plane angles during gait after TKA had greater self-reported pain and function score improvements after standard TKA. Gait analysis may aid preoperative identification of kinematic subgroups associated with self-reported improvements after TKA, and provide evidence that may inform triaging, surgical planning, and expectation management strategies.

Level of Evidence: Prognostic Level IV. See Instructions for Authors for a complete description of levels of evidence.

More than 20% of patients with knee osteoarthritis do not report clinically meaningful improvements in pain and function or satisfaction after total knee arthroplasty (TKA)[1-4], raising concerns over the potential overuse of TKA[5]. Appropriate patient selection thus requires an understanding of the symptom state most associated with meaningful improvements after arthroplasty, previously termed the "sweet spot."[3,6] While patients with worse self-reported pain and function preoperatively experience greater improvements in patient-reported outcome measures (PROMs) after TKA[3,7-9], common PROM tools lack the ability to predict optimal candidates preoperatively[3,10,11]. Used in isolation, PROMs also provide limited insights into potential underlying biomechanical mechanisms associated with whether patients fare well or poorly.

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PROM improvements after arthroplasty have been associated with baseline gait mechanics[12-14]. TKA is inherently a mechanical surgery, and gait mechanics worsen with osteoarthritis progression[15], severity seen on radiographs[16], and pain[17,18]. Objective assessment of the severity of gait features at baseline may aid in identifying functional features most associated with PROM improvements after TKA, providing important information for preoperative candidate selection and expectation management. Another aim of TKA is to improve knee function, in part by improving patient gait[19-21]. It remains unknown if patients who report poor outcomes actually demonstrate objective improvements in gait function and, furthermore, what gait function improvements are associated with PROM improvements[22]. Exploring this could motivate investigations of the efficacy of surgically targeting specific functional deficits.

We performed this explorative study to compare pre-TKA demographic and knee-joint gait mechanics (kinematic and kinetic) between patients who reported clinically meaningful improvements in pain and function after TKA (responders) and those who did not (non-responders), and to model preoperative demographics and gait features descriptive of responders. The secondary aim was to compare pre-TKA to post-TKA changes in knee-joint gait mechanics among pain and function responders and non-responders, and to examine correlations between gait changes and self-reported improvements.

Materials and Methods

Patients and Surgery

Patients with end-stage knee osteoarthritis scheduled to receive a primary TKA at a high-volume academic orthopaedic clinic from 2003 to 2016 underwent gait assessment 1 week prior to (n = 135) and 1 year after (n = 109) TKA (Fig. 1). Patients were included in the study if they were able to walk 6 m unassisted, and they were excluded if they screened positive for neurological disease or other conditions affecting their gait or ability to safely participate. The TKAs followed a standard medial parapatellar approach, with distal femoral cuts set to 5° of valgus and tibial cuts targeting neutral mechanical alignment. The measured resection technique was used to obtain a balanced flexion-extension gap. The patients received standard postoperative inpatient physiotherapy, with immediate weight-bearing. The median hospital stay was 3 days, and outpatient physiotherapy was not standardized and was optional. Informed consent was obtained from the participants according to the institution ethics board.

Gait Biomechanics

Data on age, sex, weight, height, and osteoarthritis severity graded by an orthopaedic surgeon using Kellgren-Lawrence (KL) global radiographic scores[23] were collected as part of the preoperative assessment. To perform the gait studies, infrared light-emitting markers were placed on participants according to a standardized protocol, which included 4 triads of markers attached to the pelvis, thigh, shank, and foot to establish limb-segment rigid body coordinate systems[24]. To define local anatomical joint axes, the locations of 12 anatomical landmarks were digitized during a static calibration trial and calculated relative to the triads during motion trials[24]. Participants walked along a 5-m walkway wearing comfortable shoes at a self-selected speed. Three-dimensional external ground reaction forces were recorded at 2,000 Hz with an AMTI Biomechanics

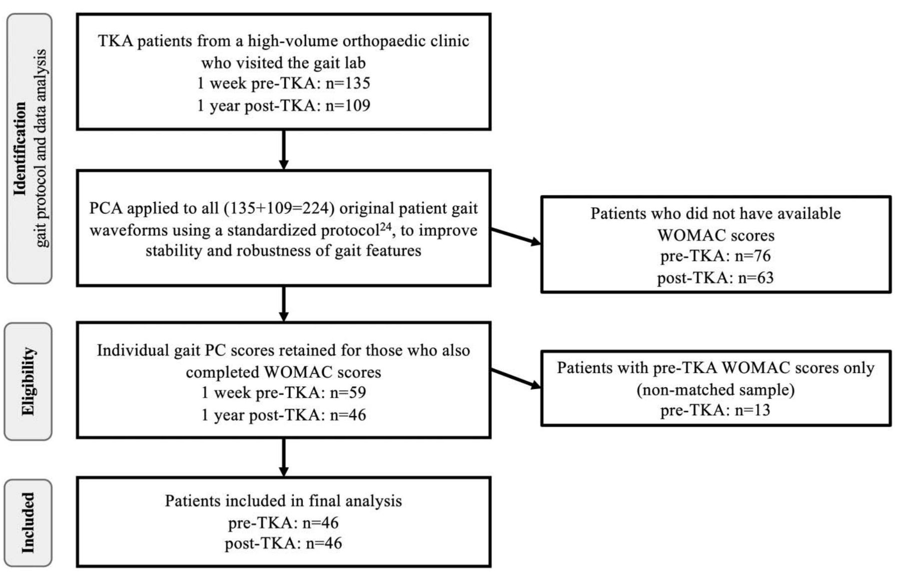

Fig. 1

CONSORT (Consolidated Standards of Reporting Trials) diagram of patient eligibility and selection processes. All participants were screened for previous lower-extremity surgery (e.g., arthroplasty in another joint) as well as neurological and other existing pathological conditions (e.g., rheumatoid arthritis) prior to recruitment for the gait study. No baseline differences in WOMAC scores were detected between subjects who did (n = 46) and those who did not (n = 13) have complete post-TKA scores in any WOMAC domain ($p > 0.5$). PCA = principal component analysis.

TABLE I Baseline Demographics and Self-Reported WOMAC Scores of Pain and Function Responders and Non-Responders

		WOMAC Pain Domain			WOMAC Physical Function Domain		
	Total	Responders	Non-Responders	P Value*	Responders	Non-Responders	P Value*
No. of subjects	46	34	12		36	10	
Sex				0.694			0.822
Male	17	12	5		13	4	
Female	29	22	7		23	6	
Age† *(yr)*	64.1 (6.6)	63.6 (7.0)	65.7 (5.4)	0.354	63.5 (6.8)	66.4 (5.7)	0.223
BMI† *(kg/m²)*	32.6 (5.7)	32.7 (6.2)	32.5 (4.0)	0.926	32.4 (6.1)	33.3 (4.1)	0.687
KL grade‡§ *(no. of subjects)*	4.0 (3, 4)	4.0 (3, 4)	3.0 (3, 3)	**0.030**	4.0 (3, 4)	3.0 (3, 3)	**0.030**
0	0	0	0		0	0	
1	0	0	0		0	0	
2	0	0	0		0	0	
3	13	9	4		9	4	
4	14	14	0		14	0	
Gait speed† *(m/s)*							
Pre-TKA	0.9 (0.2)	0.9 (0.2)	0.8 (0.2)	**0.038**	0.9 (0.2)	0.9 (0.2)	0.536
Post-TKA	1.0 (0.2)	1.1 (0.2)	1.0 (0.2)	0.232	1.1 (0.2)	1.0 (0.2)	0.153
WOMAC score‡							
Total	47.9 (21.3, 75.6)	45.5 (19.1, 71.0)	54.7 (38.2, 75.0)	**0.037**	46.1 (19.3, 70.7)	56.9 (38.3, 75.1)	0.101
Pain	50.0 (26.3, 75.0)	45.0 (24.1, 70.9)	62.5 (37.8, 78.6)	**0.007**	47.5 (24.3, 75.0)	60.0 (37.2, 77.8)	0.074
Joint stiffness	50.0 (12.5, 75.0)	50.0 (10.3, 75.0)	50.0 (19.4, 75.0)	0.082	50.0 (10.9, 75.0)	43.8 (15.3, 75.0)	0.529
Physical function	47.1 (25.6, 80.1)	44.1 (22.9, 82.4)	47.8 (35.2, 73.1)	0.197	46.9 (23.6, 74.5)	58.1 (34.7, 86.0)	0.068

*Significant ($p < 0.05$) values are in bold. †The values are given as the mean and standard deviation. ‡The values are given as the median and 95% CI. §Grades were available for 27 of the 46 participants, reasonably distributed between groups—i.e., they were available for 23 of the 34 pain responders, 4 of the 12 pain non-responders, 23 of the 36 function responders, and 4 of the 10 function non-responders.

Platform System (Advanced Medical Technology) embedded in the walkway. This was synchronized to an Optotrak opto-electronic motion capture system (NDI) sampling marker positions at 100 Hz. Knee-joint angles were calculated according to the joint coordinate system[25], and net resultant knee-joint moments were measured by inverse dynamics[26-28], amplitude normalized to body mass (Nm/kg). Following this protocol[24], a minimum of 4 walking trials were averaged and normalized for each participant to 1 gait cycle (0% to 100%) for flexion/extension angles and to stance phase (0% to 100%) for moments and adduction angles.

Principal component analysis (PCA) was used to capture major features of participant variability in knee angle and moments waveforms because it has demonstrated better sensitivity than discrete gait parameters[14,16]. A large sample of patient waveforms before (n = 135) and 1 year after (n = 109) TKA were used to create robust principal component (PC) models using a standardized protocol[29]. Three knee adduction moment, adduction angle, and flexion moment PCs and 4 knee flexion-extension angle PCs were retained (see Appendix). These features have been previously shown to describe the major modes of variability in the gait of individuals who underwent TKA[21] and those with osteoarthritis[30], or were features typically applied to functional assessment after TKA[14,31,32]. Individual patient data were projected onto each PC, providing individual subject PC scores used in hypothesis testing.

PROMs

A portion of the participants who underwent gait analysis completed the Western Ontario and McMaster Universities Osteoarthritis Index (WOMAC)[33] PROM questionnaire (scale, 0 [worst] to 100 [best]) 1 week before (n = 59) and 1 year after (n = 46) TKA, meeting international PROM collection timing standards[34]. Patients with both pre-TKA and post-TKA WOMAC scores (n = 46) were included in the analysis (Fig. 1). Pre-TKA to post-TKA improvements of ≥23 points in the WOMAC pain score and ≥19 points in the WOMAC function score were used to categorize patients, independently, as "pain responders" and "function responders," following WOMAC minimal clinically important difference (MCID) criteria[2,35]. Non-responder follow-up scores were assessed for ceiling effects (a postoperative score of 100), ensuring that the WOMAC boundaries did not contribute to non-responder classification.

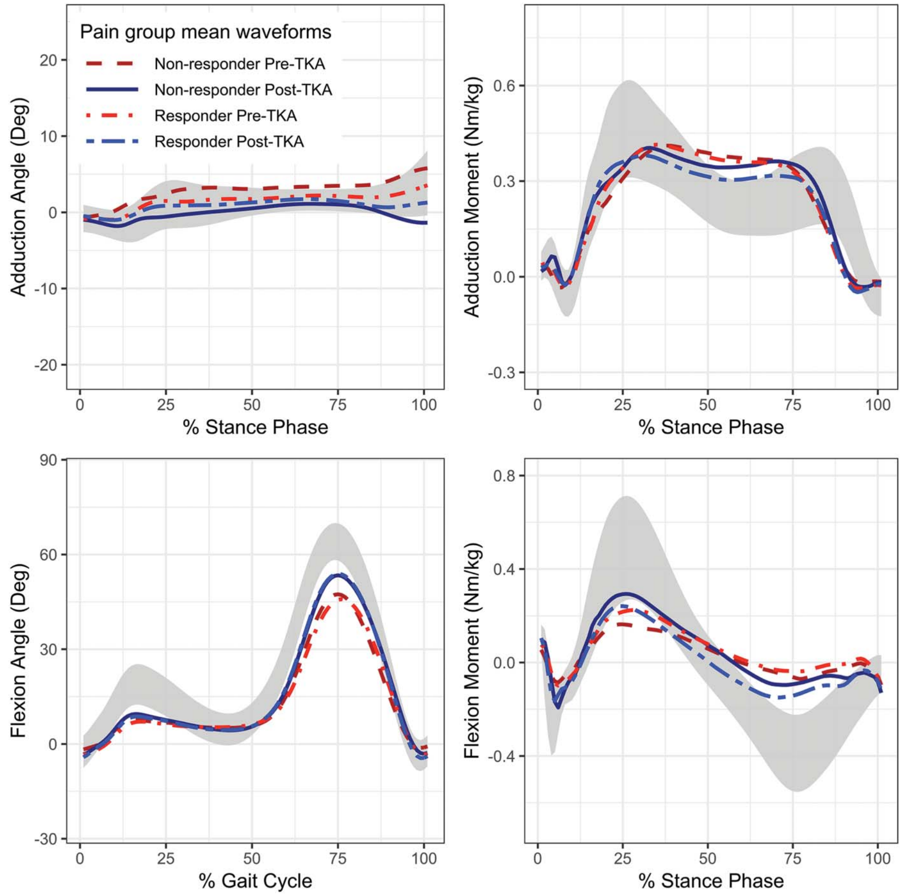

Fig. 2

Mean gait-study waveforms collected 1 week before and 1 year after TKA in the pain responder (n = 34) and non-responder (n = 12) groups. Light shaded regions represent 1 standard deviation around the mean of the gait waveforms of 209 asymptomatic adults.

Statistical Analysis

Baseline Analysis (Primary Aim)

Baseline variable (sex, age, body mass index [BMI], KL grade, WOMAC scores, and gait speed) and PC score differences between pain and function responders and non-responders were assessed with use of chi-square tests, unpaired t tests, and Mann-Whitney U tests. Correlations of baseline demographics and gait PC scores with changes in WOMAC pain and function scores (postoperative minus preoperative) were examined using Pearson correlation coefficients. Variables showing significant correlations with changes in WOMAC pain and function scores were retained for multiple regression analyses. Binomial generalized linear models were used to examine baseline demographics and baseline gait features associated with pain and function responder classification independently, assessed using the Akaike information criterion. Final models were presented using modified Poisson regression[36] for improved clinical interpretation[37], representing coefficients as relative risk ratios (RRs) and 95% confidence intervals (CIs) derived from standard errors using the robust sandwich estimator. Features were scaled (0 to 10), with a 1-point increase in RR associated with a 10% change in PC score. All analyses were conducted in an exploratory fashion with p values of <0.05 considered significant.

Pre-TKA to Post-TKA Changes (Secondary Aim)

Differences between pre-TKA and post-TKA gait features within the pain and function responder and non-responder groups were compared using paired t tests. Correlations between changes in PC scores (post-TKA minus pre-TKA) and changes in WOMAC pain and function scores were examined using Pearson correlation coefficients.

Results

Baseline Analysis

Pain

Seventy-four percent (34) of the 46 patients met the WOMAC pain domain MCID improvement criterion and were classified as pain responders; the remaining 26% (12) were classified as pain non-responders. Preoperatively, pain responders (compared with non-responders) had more severe osteoarthritis as classified radiographically (p = 0.03), were more symptomatic (median total WOMAC pain score, 45.5 [95% CI = 19.1 to 71.0] versus 54.7 [95% CI = 38.2 to 75.0], p = 0.04), and walked at faster gait speeds (mean [and standard deviation], 0.93 ± 0.19 m/s versus 0.80 ± 0.18 m/s, p = 0.04) (Table I). Pain responders also walked with a lower stance-phase adduction angle magnitude (PC1)

TABLE II Principal Component Scores of Pain Responders and Non-Responders Before and After TKA

Gait Feature	Variance Explained *(%)*	Mean (Standard Deviation): Pre-TKA Responders (N = 34)	Pre-TKA Non-Responders (N = 12)	Pre-TKA P Value*	Post-TKA Responders (N = 34)	Post-TKA Non-Responders (N = 12)	Post-TKA P Value*	P Value* for Within-Responder and Non-Responder Group Difference: Responders	Non-Responders
Flexion angle									
PC1: gait cycle flexion angle magnitude	65.09	−13.70 (57.97)	−10.55 (58.16)	0.873	21.44 (60.69)	21.35 (41.31)	0.120	**0.017**	0.137
PC2: stance-to-swing angle range	15.79	−2.23 (40.75)	−7.12 (31.53)	0.708	7.88 (31.40)	4.67 (29.45)	0.162	0.256	0.354
PC3: phase shift: timing of stance and peaks	11.91	−8.20 (31.07)	2.22 (32.64)	0.329	4.38 (22.68)	−0.99 (28.72)	0.802	0.061	0.800
PC4: stance-phase range of motion	2.60	−4.18 (12.70)	2.55 (11.83)	0.116	0.16 (11.16)	2.45 (17.43)	0.533	0.139	0.987
Adduction angle									
PC1: stance-phase adduction angle magnitude	57.40	3.10 (19.75)	17.52 (18.29)	**0.032**	−5.21 (20.04)	−15.14 (20.77)	**0.001**	0.090	**<0.001**
PC2: midstance-to-terminal stance range	24.04	3.10 (19.75)	−1.21 (9.16)	0.803	−2.02 (13.00)	−2.03 (7.53)	0.842	0.567	0.812
PC3: heel strike-to-midstance range	8.60	0.10 (17.11)	0.45 (12.01)	0.964	0.20 (5.66)	3.26 (7.79)	0.923	0.955	0.505
Flexion moment									
PC1: gait cycle flexion moment magnitude	72.59	0.08 (2.03)	−0.17 (1.62)	0.696	−0.48 (1.21)	0.01 (1.69)	0.496	0.172	0.797
PC2: stance-phase flexion moment range	16.53	−0.21 (0.63)	−0.33 (0.43)	0.572	0.19 (0.61)	0.21 (0.65)	**0.011**	**0.011**	**0.029**
PC3: phase shift: timing of flexion peaks	3.90	0.00 (0.47)	−0.01 (0.27)	0.961	0.00 (0.29)	−0.05 (0.26)	0.945	0.996	0.706
Adduction moment									
PC1: stance-phase adduction moment magnitude	83.17	0.06 (1.67)	0.05 (1.63)	0.987	−0.15 (0.88)	0.07 (0.86)	0.596	0.520	0.966
PC2: first-peak and midstance range	8.40	−0.14 (0.33)	−0.28 (0.40)	0.238	0.09 (0.34)	−0.09 (0.36)	**0.003**	**0.006**	0.221
PC3: midstance and second-peak range	3.20	−0.07 (0.27)	−0.08 (0.31)	0.892	0.13 (0.23)	0.17 (0.32)	**0.016**	**0.002**	0.064

*Significant ($p < 0.05$) values are in bold.

relative to pain non-responders preoperatively ($p = 0.03$), indicating lower overall knee adduction angle magnitudes (less consistently varus) throughout the stance phase of gait (Fig. 2, Table II).

Patients who had less stance-phase flexion-extension angle range (PC4: $r = -0.32$, $p = 0.03$) and a lower stance-phase varus (adduction angle) magnitude (PC1: $r = -0.37$, $p = 0.01$) preoperatively had more improvement in WOMAC pain scores (Figs. 3-A and 3-B). In multivariate modeling, lower stance-phase varus (adduction angle) magnitude was the only preoperative feature predictive of being a pain responder (PC1: RR = 0.92, $p < 0.05$) (Table III).

Function

Seventy-eight percent (36) of the 46 patients met the WOMAC function domain MCID improvement criterion and were classified as function responders; the remaining 22% (10) were classified as function non-responders. Preoperatively, function responders had more severe osteoarthritis as classified radiographically ($p = 0.03$) than function non-responders (Table I). Function responders also had a lower stance-phase varus (adduction angle) magnitude (PC1: $p < 0.05$) and less stance-phase flexion-extension angle range than non-responders (PC4: $p = 0.01$) preoperatively (Fig. 4, Table IV).

Patients who were younger ($r = -0.41$, $p = 0.005$), had less stance-phase flexion-extension angle range (PC4: $r = -0.38$, $p = 0.009$), and had a lower stance-phase varus (adduction angle) magnitude (PC1: $r = -0.34$, $p = 0.01$) preoperatively had more improvement in WOMAC function scores (Figs. 3-D, 3-E, and 3-F). In multivariate modeling, the likelihood of being a function responder increased only if the patient walked with less stance-phase flexion-extension angle range preoperatively (PC4: RR = 0.90, $p = 0.01$) (Table III).

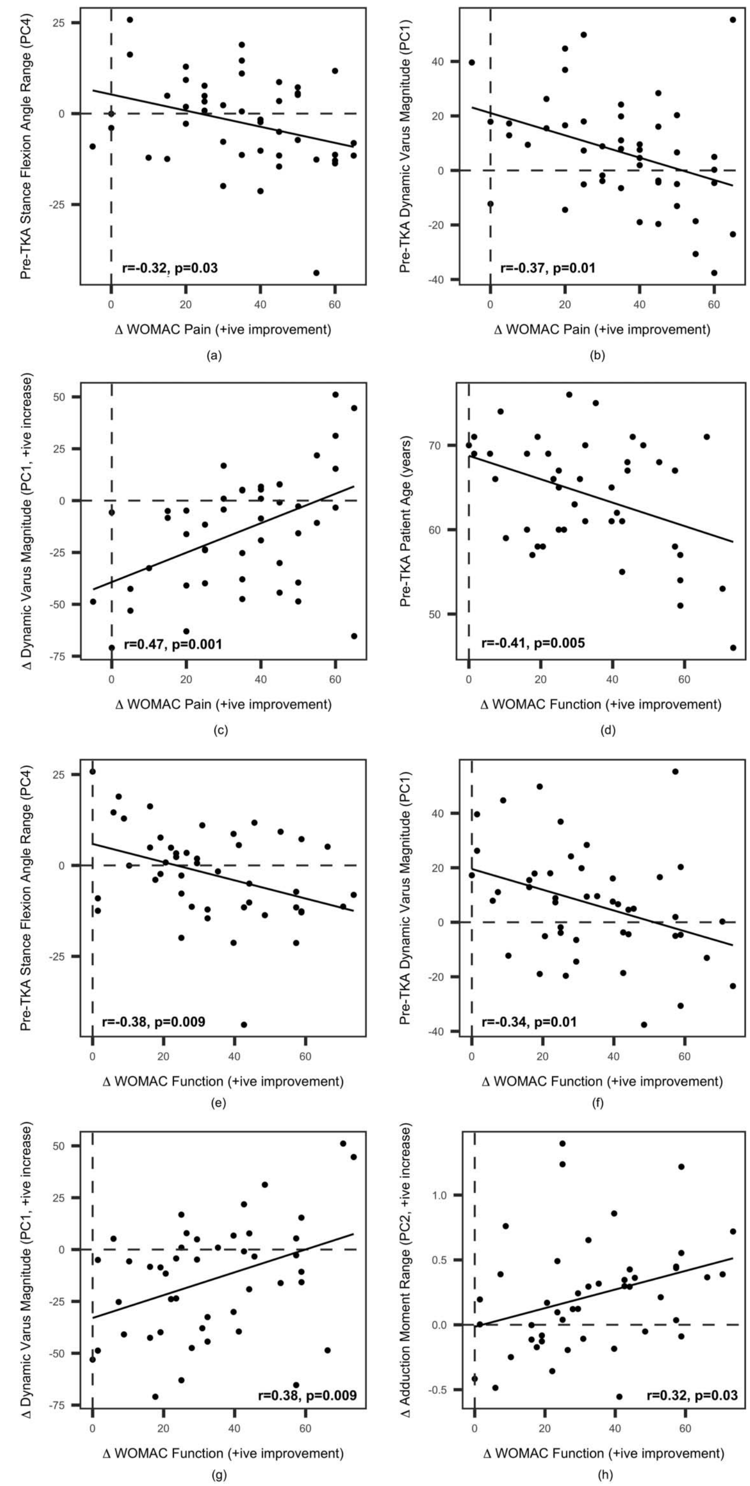

Fig. 3

Figs. 3-A through 3-H Associations of demographic and gait features with pre-TKA to post-TKA changes in WOMAC pain and function scores. **Figs. 3-C and 3-G** Positive (+ive) changes in stance-phase varus (adduction angle) magnitude (PC1) represent an increase in varus alignment during stance while negative changes represent more varus magnitude reduction (varus-to-valgus change). Lower stance-phase varus magnitudes at baseline and less pre-TKA to post-TKA reduction in stance-phase varus magnitude after TKA were each independently associated with more self-reported improvements in pain and function. **Fig. 3-H** Positive changes in the adduction moment range (PC2) represent a larger medial compartment loading/unloading range during stance. Larger increases in the dynamic loading range were associated with more improvement in self-reported function.

TABLE III Baseline and Change in Gait Features Contributing to Clinically Meaningful Improvements in Self-Reported Pain and Function*

	RR	95% CI	Estimate	Std. Error	P Value†
Pain domain (r^2 = 0.14‡)					
Adduction angle PC1: pre-TKA magnitude of stance-phase varus alignment	0.915	0.838, 0.998	−0.089	0.045	**0.046**
Function domain (r^2 = 0.15‡)					
Flexion angle PC4: pre-TKA flexion angle range of motion during stance	0.898	0.827, 0.976	−0.107	0.042	**0.011**

*From multivariate modified Poisson regression analysis. Items were scaled (0 to 10), with a 1-point increase in RR associated with a 10% change in PC score. †Significant ($p < 0.05$) values are in bold. ‡Linear models were applied using the magnitude of WOMAC domain improvement as the independent variable to provide estimates of r^2.

Pre-TKA to Post-TKA Changes

Pain and function responders demonstrated typically reported pre-TKA to post-TKA gait improvements[21,38] (toward being asymptomatic) in terms of the magnitude and pattern of adduction moment, flexion moment, and flexion angle features (Tables II and IV). The only gait change captured in both the pain and function non-responder groups was a reduction in the stance-phase varus (adduction angle) magnitude after TKA relative to preoperatively (PC1: $p \leq 0.005$; Figs. 2 and 4 and Tables II and IV). Pain non-responders alone also showed more stance-phase flexion moment range after TKA relative to preoperatively (PC2: p = 0.03, Table II).

Patients who experienced less pre-TKA to post-TKA reduction in the stance-phase varus (adduction angle) magnitude (ΔPC1: r = 0.47, p = 0.001) had more improvement in WOMAC pain scores (Fig. 3-C). Patients who experienced less reduction in the stance-phase varus (adduction angle) magnitude after the TKA (ΔPC1: r = 0.38, p = 0.009) and showed a

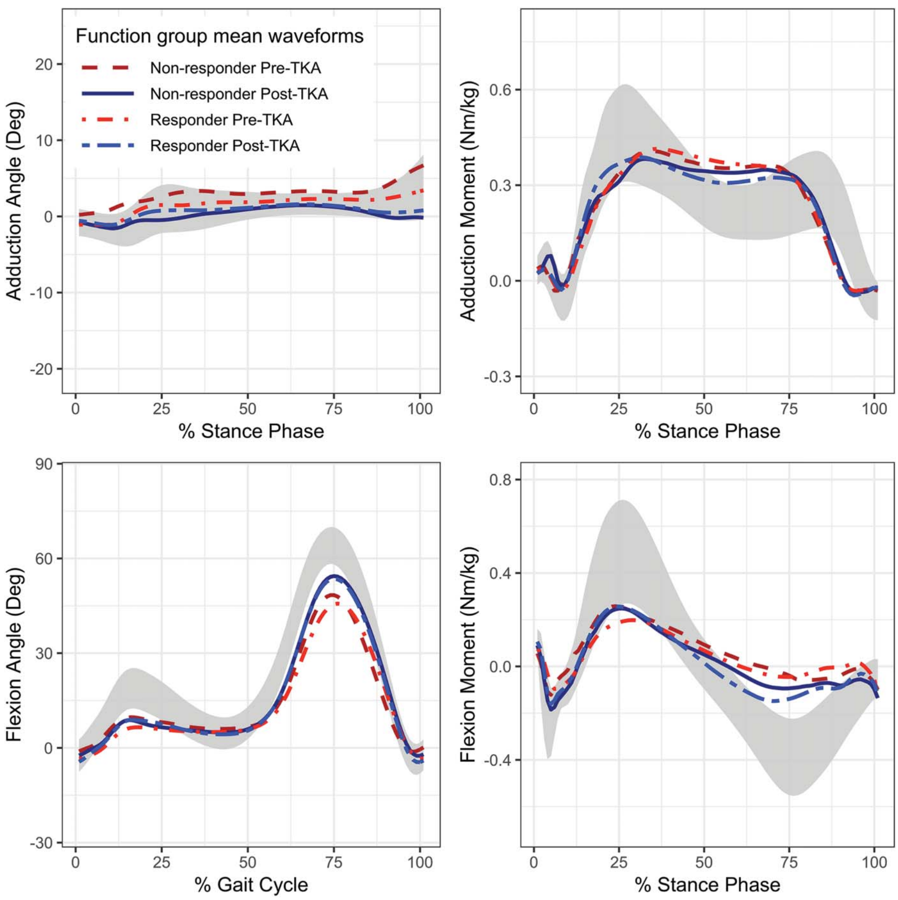

Fig. 4

Mean gait-study waveforms collected 1 week before TKA and 1 year after TKA in the function responder (n = 36) and non-responder (n = 10) groups. Light shaded regions represent 1 standard deviation around the mean gait waveforms of 209 asymptomatic adults.

TABLE IV Principal Component Scores of Function Responders and Non-Responders Before and After TKA

Gait Feature	Variance Explained *(%)*	Mean (Standard Deviation) Pre-TKA Responders (N = 36)	Pre-TKA Non-Responders (N = 10)	Pre-TKA P Value*	Post-TKA Responders (N = 36)	Post-TKA Non-Responders (N = 10)	Post-TKA P Value*	P Value* for Within-Responder and Non-Responder Group Difference: Responders	P Value* for Within-Responder and Non-Responder Group Difference: Non-Responders
Flexion angle									
PC1: gait cycle flexion angle magnitude	65.09	−14.90 (56.42)	−5.59 (63.33)	0.655	20.43 (58.94)	24.96 (45.40)	0.231	**0.011**	0.233
PC2: stance-to-swing angle range	15.79	−0.33 (40.32)	−14.92 (28.65)	0.291	7.06 (28.97)	6.98 (37.71)	**0.039**	0.375	0.162
PC3: phase shift: timing of stance and peaks	11.91	−8.91 (30.64)	6.86 (32.91)	0.163	3.89 (24.13)	−0.29 (25.38)	0.752	0.053	0.593
PC4: stance-phase range of motion	2.60	−4.99 (11.58)	6.78 (12.84)	**0.008**	0.95 (10.85)	0.06 (19.36)	0.155	**0.028**	0.374
Adduction angle									
PC1: stance-phase adduction angle magnitude	57.40	3.75 (20.31)	18.07 (16.15)	**0.046**	−6.79 (19.81)	−11.47 (23.49)	**0.001**	**0.029**	**0.005**
PC2: midstance-to-terminal stance range	24.04	0.02 (16.64)	−1.18 (10.03)	0.829	−2.24 (12.82)	−1.26 (7.02)	0.811	0.521	0.985
PC3: heel strike-to-midstance range	8.60	1.21 (9.91)	−2.79 (8.69)	0.254	0.49 (5.95)	2.83 (7.62)	0.173	0.710	0.142
Flexion moment									
PC1: gait cycle flexion moment magnitude	72.59	−0.03 (1.99)	0.18 (1.68)	0.762	−0.39 (1.23)	−0.20 (1.80)	0.234	0.355	0.627
PC2: stance-phase flexion moment range	16.53	−0.29 (0.56)	−0.07 (0.66)	0.303	0.24 (0.57)	0.03 (0.77)	0.151	**<0.001**	0.764
PC3: phase shift: timing of flexion peaks	3.90	0.00 (0.43)	0.01 (0.45)	0.951	0.01 (0.29)	−0.08 (0.27)	0.994	0.919	0.625
Adduction moment									
PC1: stance-phase adduction moment magnitude	83.17	0.06 (1.64)	0.04 (1.73)	0.962	−0.10 (0.85)	−0.05 (0.99)	0.726	0.593	0.890
PC2: first-peak and midstance range	8.40	−0.19 (0.38)	−0.12 (0.27)	0.598	0.10 (0.35)	−0.13 (0.31)	0.069	**0.001**	0.944
PC3: midstance and second-peak range	3.20	−0.08 (0.26)	−0.04 (0.36)	0.640	0.15 (0.24)	0.13 (0.31)	0.068	**<0.001**	0.290

*Significant ($p < 0.05$) values are in bold.

larger increase in the early to mid-stance adduction moment range (ΔPC2: $r = 0.32$, $p = 0.03$) had more improvement in WOMAC function scores (Figs. 3-G and 3-H).

Discussion

Patients who responded to TKA in terms of improvement in function (function responders) were characterized biomechanically by less stance-phase flexion-extension angle range and lower adduction angle magnitude preoperatively (Fig. 4, Table IV). In multivariate modeling, less stance-phase flexion-extension angle range was the only feature predictive of being a function responder (Table III). This finding is in agreement with a similar study by Naili et al. (n = 28), who reported less sagittal-plane knee-angle range before TKA in patients who met the minimal detectable change criterion for improvement in knee-related quality-of-life scores postoperatively compared with those who did not (stance to swing, 45° ± 6° versus 52° ± 5°)[13]. Less sagittal range is typically associated with "more severe," or stiffer, sagittal plane kinematics, resembling more severe osteoarthritis pattern norms[15,30] (Fig. 4). Younger age was also associated with more improvement in WOMAC function scores in our univariate analysis ($r = -0.41$, $p = 0.005$) (Fig. 3). Although younger patients typically report less satisfaction after TKA[39], they have been found to have more self-reported improvements[39,40], attributed to improved functional abilities captured within activities of daily living scores. Of the 5 function responders who were ≤55 years old in this study, 4 demonstrated stance-phase flexion-extension angle ranges (PC4) below the norm preoperatively, potentially representing a subset of young patients with stiff sagittal kinematics. Stiff kinematics, coupled with radiographic evidence of more severe osteoarthritis ($p = 0.03$), and trends toward greater symptom severity (Table I) align with previous inferences that patients with more severe preoperative problems (typically measured by PROMs) tend to have better arthroplasty outcomes[3,7,8,13]. Our study suggests that severity could be captured objectively by measuring knee kinematics during gait. Furthermore, these kinematic features could be detectable in clinical settings through simple wearable or markerless motion capture.

The only biomechanical gait feature descriptive of pain responders before TKA was a lower stance-phase varus (adduction angle) magnitude, suggested by comparative tests and in multivariate modeling (Tables II and III). Conversely, pain non-responders appeared more varus during stance preoperatively. While static and dynamic varus alignment have both been associated with more severe medial compartment osteoarthritis[8,41,42], less severe osteoarthritis seen on radiographs and less symptom severity in pain non-responders (Table I) suggest a potential kinematic subgroup of individuals with constitutional varus alignment[43] or kinematic varus[44]. Although interesting, these results should be interpreted with caution. Our exploratory approach did not account for multiple comparisons. This, coupled with small non-responder group sizes, increased the possibility of type-I errors and resulted in large CIs around our estimates. However, visualizations of kinematic data did suggest that 10 of 12 pain responders and 9 of 10 function non-responders had preoperative varus angle magnitudes above the norm. If the soft tissue and muscle surrounding the joint have adapted to native varus kinematics[45], mechanics after standard arthroplasty might be perceived by the patient as unnatural, potentially contributing to less self-reported improvements in pain and function. It has been suggested that standardized alignment may not be optimal for all patients[46-48]. Vanlommel et al.[48] reported significantly better function and knee scores in individuals with preoperative varus when postoperative alignment remained in mild varus. Under these assumptions, native varus magnitudes might be a false signal during selection of patients for arthroplasty, or this presentation with an absence of other severe osteoarthritic features might characterize clinical candidate subgroups for whom neutral corrections are not "clinically relevant."[22] Investigating patient biomechanical variability with respect to outcomes in larger studies is an important area for further research. These groups might benefit from altered clinical or surgical approaches (such as individualized alignment or a high tibial osteotomy), relative to standard-of-care arthroplasty.

Patients who report less pain and function improvement postoperatively appear to demonstrate less objective functional improvements during gait. Non-responders showed significantly reduced stance-phase varus angles after TKA, yet lagged in terms of sagittal kinematic and kinetic loading pattern corrections typically reported in population-average studies (Tables II and IV)[14,21,32,38]. Naili et al. proposed that poor patient-reported outcomes might be partially explained by a lack of dynamic kinematic and kinetic corrections, despite alignment corrections in the frontal plane, a feature that surgery may be most able to address biomechanically[13]. Although our results suggested less 3-dimensional corrections in non-responders overall (Tables II and IV), we did find frontal plane changes to be associated with self-reported improvement in pain and function. Specifically, *less* reduction in stance-phase varus (adduction angle) magnitude was independently associated with more improvement in PROM scores (in both the pain and function domains), as were *larger* increases in dynamic frontal plane loading (PC2) (in the function domain alone) (Fig. 3). This was a unique finding, supporting our interpretation that standard arthroplasty might not be optimal for a subset of patients. Post-hoc tests also showed no difference among the 5 surgeons in terms of the magnitude of varus reduction that they imposed ($p \geq 0.8$). Further work should be done to investigate if individualized approaches to frontal plane mechanics during surgery and rehabilitation have benefits in terms of 3-dimensional gait features that are not consistently addressed in non-responders by standard arthroplasty.

Despite including a relatively large 3-dimensional gait-analysis sample, our study had fewer non-responders than responders, making it difficult to generalize our results to the TKA population. We instead aimed to provide insights through the linkage of comprehensive biomechanical and clinical data sets and to share valuable information to guide targeted research. Our exploratory approach did not correct for multiple comparisons, and results should be interpreted as preliminary evidence of patient subgroups that may benefit from altered treatment approaches. Furthermore, the power of our ability to detect pre-TKA to post-TKA gait changes among non-responders was low (9% to 32%). However, small permutations between pain and function non-responder groups (non-responder overlap of 8 of 12 and 8 of 10, respectively) operated as a natural sensitivity analysis, improving confidence in the findings reported in both domains. Radiographs to determine the KL grade were not available for all individuals, nor were whole-leg standing radiographs, limiting our ability to translate stance-phase findings to the static alignment that is traditionally considered surgically. Using MCID thresholds to dichotomize outcomes was also not without limitations. MCID thresholds are not applicable for measuring individual change for all patients, nor do they translate well to global metrics such as satisfaction[39,49]. Furthermore, MCIDs can be influenced by preoperative symptom severity[50], and questionnaire ceiling effects may restrict rates of patients meeting MCID thresholds, despite their still having improvement. Still, PROM responsiveness scores have been recommended by the International Society of Arthroplasty Registries Working Group[51] and others[35], due to their ability to improve interpretation of within and between-patient score changes from interventions. Pain and function domains were selected as they tend to be key outcomes assessed after TKA and they are the domains most associated with satisfaction[52]. Seventy-four percent and 78% of patients met MCID thresholds for pain and function response, respectively, which is greater than in a previous Canadian study[3] but aligns closely with other studies[1,2,39] and with the 20% dissatisfaction rate typically reported after TKA[53]. WOMAC pain and function domains also tend to be less susceptible to floor and ceiling effects than joint stiffness[54]; none of the non-responders in our study reached ceilings postoperatively.

This study contributes to the growing body of evidence that suggests variability in patient-reported outcomes may be partially explained by a combination of clinical and objectively measured knee-joint biomechanical factors. Specifically, more "severe" objective gait features preoperatively tended to be associated with a larger potential for both objective and self-reported functional improvements[13]. Unique findings in this study included preliminary evidence of a varus kinematic subgroup that may be susceptible to less pain and function improvements from standard arthroplasty, and that larger reductions in stance-phase varus alignment may be unfavorable to some patients. These trends warrant further investigation. Objective functional assessment preoperatively may aid in identifying the optimal functional state (the "sweet spot") associated with patient-reported improvements and help identify those who may benefit from an individualized approach, informing triaging, surgical planning, and expectation management strategies. Our findings support the notion that TKA innovation depends on a better understanding of 3-dimensional knee mechanics at an individual level to provide expected improvements for all patients.

Appendix

eA Supporting material provided by the authors is posted with the online version of this article as a data supplement at jbjs.org (http://links.lww.com/JBJSOA/A152). ■

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